以遺傳演算法重建二維介質柱體的微波影像
Microwave Imaging of a Two-Dimentional Dielectric Cylinder Using Genetic Algorithm

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中文摘要

本計劃將利用遺傳演算法則重建一個二維柱體的截面形狀及內部結構(介電分佈)，這屬微波影像的範疇。亦即利用一個 TM 的微波照射在一個介電分布及形狀皆未知的物體，吾人可測得外部的散射場，經由對此散射場做適當的處理，可以得知此物體的形狀及介電分佈情形。我們將研究的待測物是一個任意形狀的柱體，且該物體可以是單層或多層的結構，而其介電分佈則可為均勻或不均勻(含矩形，圓形及不規則形）。

研究計劃可區分為正散射及逆散射兩大部份，在正散射的理論方面，吾人將使用等效電流及 Dyadic 格林函數的技巧，藉此，吾人可導出一組非線性積分方程式，然後使用典型的動差法來解此積分方程以計算出散射場。

在逆散射部份，吾人將採用遺傳演算法則並配合吾人提出的一種全新的概念來重建該柱體的介電分佈與截面形狀。傳統的方法常常受困於 ill-condition/noise 的問題或須良好的初始值(initial guess)，因此重建結果並不能真正令人滿意。特別是當切割愈細，未知數增加時，所花時間亦成比例增加，但效果卻不見改善。本研究利用遺傳演算法則所具有的全域收斂的特性，能克服上述的諸多困擾而重建一良好的影像

由於利用遺傳演算法則最佳化時，通常所需迭代的代數較多且所需的目標函數之計算次數也較多。為了減少計算時間，故在參數的選取上，吾人將提出兩種新的技巧 -regular shape expansion scheme and shape mutation scheme 以減少參數的個數，基因(gene)的個數也隨之減少，以使收斂時間縮短在可接受的範圍內。

關鍵詞：微波影像，逆散射，遺傳演算法則會

Abstract

A computational method combining the genetic algorithm (GA) and a two-phase technique is reported for electromagnetic imaging of a homogeneous and/or multi-cylinder dielectric object of arbitrary shape. By measuring the scattered field, the shape, location, size and permittivity of the object are retrieved quite successfully. The forward problem is solved based on the equivalent source current and the method of moments (MoM), while the inverse problem is reformulated into an optimization one, and is solved by the proposed scheme. It is found that the proposed two-phase technique converges faster than a previously reported method using shape mutation scheme does. Numerical simulation shows that good reconstruction can be obtained for a homogeneous and/or multiple-cylinder object as long as the noise level is $\leq$-20dB.

Keywords: Microwave Imaging, Inverse Scattering , Genetic Algorithm

1. Introduction

To retrieve the shape, location, size and the internal property of an object embedded in a homogeneous space or buried underground via electromagnetic scattering had gained increasing interest in many areas such as non-destructive evaluation, geophysics, biomedical application, material engineering and environmental investigations, etc. We have previously reported a method combining GA and shape mutation scheme for inverse scattering of a homogeneous dielectric cylinder[1]. In this paper, we proposed an improved technique to achieve faster convergence. The inverse problem is easier when the object is homogeneous and the permittivity is known, plus some priori topological information of the object is given. But if the permittivity is assumed unknown and a priori topological information is missing, the shape identification problem remains difficult, because the relationship between the scattered field and the shape and/or permittivity of the object is strongly nonlinear. Here, we focus on the identification of a 2-D penetrable homogeneous object, which is embedded in a homogeneous space. A TM electromagnetic wave is cast in a test object domain to characterize the permittivity, shape, location and size of the object.

In this case, traditional methods appear to be limited to the identification of a single isolated cylinder unless appropriate information on the number and location of the unknown cylinders is used. Most traditional iterative inverse algorithms are founded on a functional minimization via some gradient-type scheme, such as Newton-Kantorovitch method [2-4], Levenberg-Marquardt algorithm [5-7], and conjugate-gradient method [8]. In general, during the search of the global minimum, they tend to get trapped in local minima when the initial guess is far from the exact one. Besides, some priori topological information or regulation methods are usually enforced to overcome the ill-posedness. When only lesser topological constraints can be enforced, there are methods that use neural network [9] or level-set modeling [10,11] reported.

In this paper, GA is applied to reconstruct a dielectric object through a two-phase technique. GA is recognized as a global optimization technique based on the evolutionary mechanism of natural selection. It searches through a coded parameter space randomly using three main operations, named crossover, mutation and selection, and tends to yield global extreme solution [12,13]. In accordance with the two-phase technique, GA is found quite suited for the inversion of the above multi-cylinder object. In sections 2 and 3 the theoretical formulation and the inverse scheme are presented. The idea of regular shape expansion is introduced to work with GA for phase I. The definition of the inner and outer boundary cells for shape mutation is introduced in this paper such that shape splitting and/or shape combining are possible during the course of phase II. Thus, the proposed method can be successfully applied to reconstruct objects consisting of multiple cylinders. In section 3, dielectric objects with arbitrary cross-section shape are considered. The numerical experiments for shape and permittivity reconstruction are found quite good. The effects on the inversion due to random noise are also reported. Good inversion is ensured as long as the noise level is≤-20dB.

2. Theoretical Formulation

Consider a homogeneous dielectric object (possibly with multiple cylinders) of arbitrary cross section in free space as shown in Fig.1, in which the object is assumed infinitive long and homogeneous in z-direction. The object is illuminated by an incident electromagnetic plane wave of TM polarization, i.e. $\vec{E}$ is parallel to z-axis. The forward problem can be analyzed using the concept of equivalent current $\vec{J}_{eq}$ such that the scattered field outside the cylinder can be expressed by

$$E_z^s(\vec{r}) = \int_s G(\vec{r},\vec{r}')k_0^2(\varepsilon_r - 1)E_Z(\vec{r}')ds' \qquad \ldots(1)$$

where k_0 is the wavenumber in free space and

$$G(\vec{r},\vec{r}') = \frac{-j}{4}H_0^{(2)}(k_0\,|\vec{r}-\vec{r}'|) \qquad \ldots(2)$$

is the two-dimensional Green's function for the free space, and $H_0^{(2)}$ is the Hankel function of the second kind with order zero. E_Z is the total internal field inside the cylinder that can be solved by the following EFIE

$$-E_Z^i(\vec{r}) = \int_s G(\vec{r},\vec{r}')k_0^2(\varepsilon_r - 1)E_z(\vec{r}')ds' - E_z(\vec{r}) \qquad \ldots(3)$$

For the forward problem, the method of moments is applied to solve (3) and then the scattered field E_z^s is calculated by (1) when the geometrical parameters and the dielectric properties of the object are given. Conversely, if we obtain sufficient information from the measured scattered field, we should be able to reconstruct the permittivity, shape, location and size of the object.

To numerically calculate the scattered field, we first divide the test domain of dielectric object into N sufficient small cells such that the relative permittivity distribution and the electric field can be written as

$$\varepsilon_r(x',y') = \sum_{n=1}^{N} \varepsilon_m P_n(x',y')$$

$$E_z(x',y') = \sum_{n=1}^{N} E_{zn} P_n(x',y')$$

where P_n, n=1~N, are the pulse functions.

Then, using the method of moments with point matching procedures, we can transform the EFIE(3) and Eq.(1) into a system of algebraic equations, respectively, as follows:

$$-[E_z^i] = \{[G_1][\tau_Z]-[I]\}\,[E_z] \qquad \ldots(4)$$

and

$$[E_z^s] = [G_2][\tau_Z]\,[E_z] \qquad \ldots(5)$$

Where $[E_z]$ and $[E_z^s]$ represent the N element total field column vector and the M element scattered field column vector, respectively. Here M is the number of the measurement points. The elements of $[G_1]$ and $[G_2]$ can be obtained via tedious mathematical manipulation. $[G_1]$ is an N×N square matrix, and $[G_2]$ is an M×N matrix. $[\tau_Z]$ is an N×N diagonal matrix with diagonal element $\tau_{Zn}=\varepsilon_m-1$.

Equations (4) and (5) are called the forward scattering formulas. If the permittivity of each cell is given, the total field inside the test domain and the outside scattered fields can be calculated directly.

3. Inverse Scheme

For the inverse problem, we have previously reported a method combining GA with shape mutation scheme to reconstruct hollow or multi-cylinder objects [1]. Using shape mutation scheme along with GA, we have successfully applied the method to retrieve the shape, size and permittivity of various dielectric objects starting from some initial population with uniform permittivity profile. However it is recognized that the method can converge faster if some better initial population are provided. In this paper, a two-phase method combining the ideas of GA with shape expansion scheme and shape mutation scheme is first reported. The output population of GA with regular shape expansion scheme in phase I are employed as the initial population of GA with shape mutation scheme in phase II for faster convergence. GA is an optimization technique that models the natural processes of evolution and selection via genetic recombination, of which the flow chart is given in Fig.2 [11]. The philosophy undergoing is the survival of more fit, thus GA tends to yield the global minimum and is suitable for the inverse problem being investigated. For the first half generations of GA, called phase I, the regular shape expansion method is introduced to work with GA. As depicted in Fig.3, the idea of regular shape expansion is to expand an arbitrary multi-layer object in terms of some possibly overlapped regular-shape cylinders – only rectangles are used in this paper. The computation idea of cell permittivities for the overlapped and non-overlapped regions is also shown in Fig.3. Note that in order to identify each regular/rectangular dielectric cylinder used in shape expansion, there are five parameters to be determined, as shown in Fig.4. They are the center coordinated (x_0, y_0), the width ,the height, and the permittivity of the rectangular cylinder. For the second half generations of GA, called phase II, the shape mutation scheme is employed to work with GA. For each generation, with shape mutation scheme, the permittivity values are changed by crossover and mutation operations, while the shape (boundary) of each individual is allowed to mutate in two directions, i.e. to extend and/or to contract the cylinder, in a random way. Then better species are selected into next generation as a typical GA does and they will finally converge to the global optimum.

In order to mutate the shape, the outer boundary cells and the inner bounder cells associated with a cylinder are defined first, as depicted in Fig.5. An inner boundary cell is in the cylinder region while its nearby 4 cells are not all in the cylinder region. Conversely, an outer boundary cell is in the air region and its nearby 4 cells are not all in the air region. To mutate the shape, the outer boundary cells and inner boundary cells of each object are recognized and kept in stacks first. To extend the cylinder, at least one of the outer boundary cells must mutate and become an inner boundary cell. On the other hand, the inner boundary cells may mutate and become outer boundary cells in order to contract the cylinder. In either way, the outer boundary cells and inner boundary cells should be updated right after each cell-mutation to make sure the shape mutation scheme working properly which requires tedious computer programming in general. Note that each individual object is allowed to contract some boundary cells and extent other boundary cells within one generation for faster convergence.

Without any priori topological information, the proposed two-phase method can yield the correct permittivity, shape, position and size of an unknown object beginning with some randomly generated population.

4. Numerical Results

The reconstruction of various homogeneous objects illuminated by an electromagnetic TM plane wave is presented. The frequency of the incident wave is 3GHz, i.e. the wavelength is 0.1 m. The test domain is $0.03 \times 0.03\ m^2$ and is divided into 12×12 small cells for inversion. The scattered field is measured in the air along a circle of radius 0.3m around the object. To ensure that the number of independent data measured exceeds the number of independent parameters, the object is illuminated by the incident waves from six different directions, and 60 measurement points of equal spacing along the circle are used for each incident angle. There are totally 360 measured data used in each inversion.

For numerical simulation purposes, the scattered E field is obtained by solving (4) and (5) with 24×24 divisions for test domain, and then some noise is added to the scattered E field to mimic realistic data that may be measured experimentally instead. Then the proposed two-phase method is used to solve the inverse problem, for which the GA parameters used are 500 for population size, 0.8 for crossover probability, and 15 for coding length. The mutation probabilities are 0.01 and 0.1 for phase I and phase II, respectively.

We now present the reconstructing results of several examples, for which the added noise levels are $\sim 10^{-5}$. Figure 6 shows the shapes of 4 dielectric cylindrical objects investigated all with relative permittivity 4. Figures 7(a) and (b) show the reconstructed details for object A for phase I and phase II, respectively, with relative error 1% for relative permittivity in final. Note that fifty generations are used for phase I, of which the final population are used as the initial population (generation zero) of phase II. In phase II, another twenty generations are needed to ensure the convergence of the shape and the permittivity. The shape error and permittivity error versus generation are shown in Fig.8, where the shape error is defined as the ratio of the number of cylinder cells at the right position over the number of cylinder cells of desired shape. It is found that the object shape usually converges faster than the permittivity does, which is quite reasonable. This demonstrates that the proposed method works quite well for an object consisting of multiple cylinders. In Figs. 9(a) and (b), the reconstructed details for the triangular object B are shown. Similarly, fifty generations are used for phase I, while twenty generations are needed for phase II. Figure 10 shows the shape error and permittivity error versus generation. As compared to the results obtained by shape mutation scheme only [1], the improvement achieved by the present method is about 20% for the above two objects. In general, it is found that the improvement for various testing objects by using the two-phase technique is from 10% to 75%. As a third example, the reconstructed results for object C are shown in Figs. 11(a) and (b). The shape and permittivity errors decrease similarly and are omitted here for brevity. To investigate the effects of noise upon the reconstruction quality by using this method, Gaussian random noise with zero mean is intentionally added to the scattered field and the reconstructed error against noise level is plotted as shown in Fig.12. It is obvious that the objects can be reconstructed quite well with permittivity error$\leq$7% as long as the relative noise level is$\leq$0.1(-20dB), which is a quite satisfactory result.

It should be noted that the inversion still is a time consuming process since GA requires a lot of function calls (500 in our case) per generation, and each function call is computationally expensive for this kind of problem. However, this maybe largely improved if parallel GA is implemented. Thus the present two-phase technique is well suited for inversion of a homogeneous dielectric object with arbitrary shape. Furthermore, the shape expansion scheme itself can work alone with GA and be applied for the inversion of multi-layer or inhomogeneous dielectric objects.

5. Conclusion

We have reported a two-phase technique combing GA, shape expansion scheme and shape mutation scheme, which is applied to reconstruct the shape, location, size and permittivity of a homogeneous and/or multiple-cylinder dielectric object quite successfully. It is shown that this method always converges to the global optimum without any priori topological information while other gradient-type methods usually get trapped in local extremes. The inclusion of phase I to provide better initial guess for phase II can improve the convergence by 10%~75%. Besides, good reconstruction is achieved even when the scattered field is contaminated with random noise. Numerical simulation shows that any homogeneous and/or multiple-cylinder object can be reconstructed quite well as long as the noise level is $\leq$-20dB. Future works may incorporate parallel GA to accelerate the inversion process. Also, the shape expansion scheme will be applied to reconstructed multi-layer dielectric objects.

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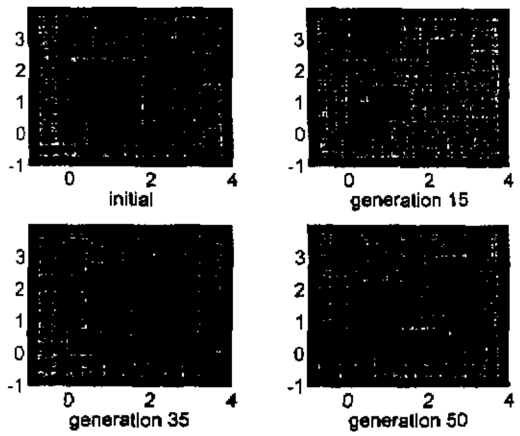

Fig.7 Reconstructed shapes at different generations for object A in (a)phase I, and (b) phase II

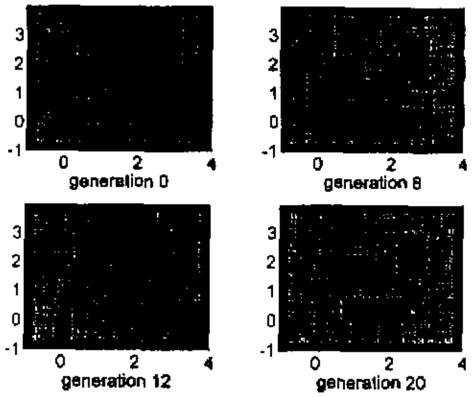

Fig.7 (b) (continued)

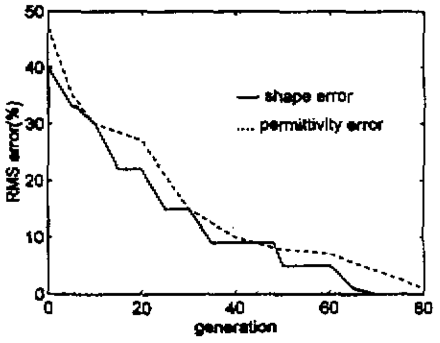

Fig.8 The shape error and permittivity error versus generation for object A.

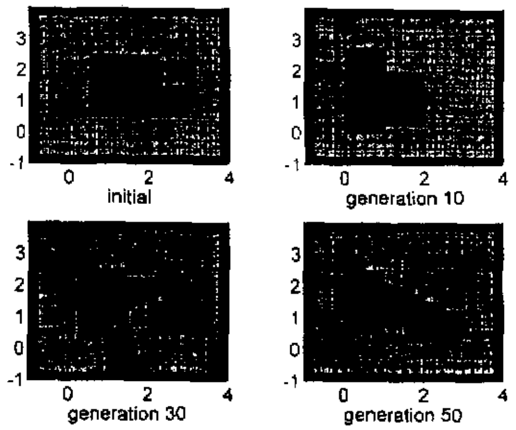

Fig.9 Reconstructed shapes at different generations for object B in (a)phase I, and (b) phase II

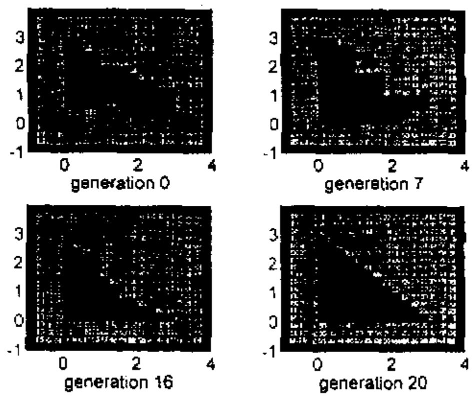

Fig.9 (b) (continued)

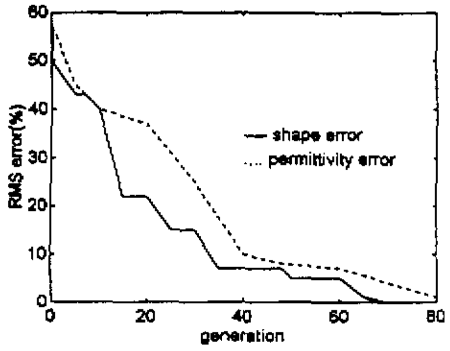

Fig.10 The shape error and permittivity error versus generation for object B.

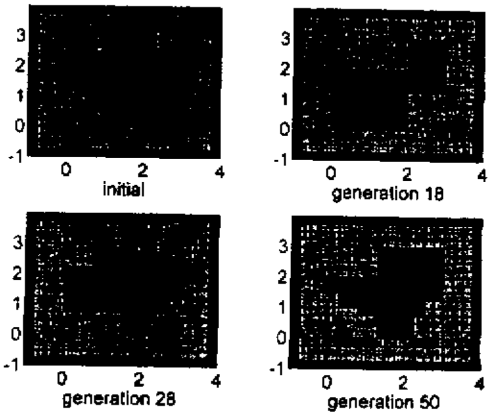

Fig.11 Reconstructed shapes at different generati
for object C in (a)phase I, and (b) phase II

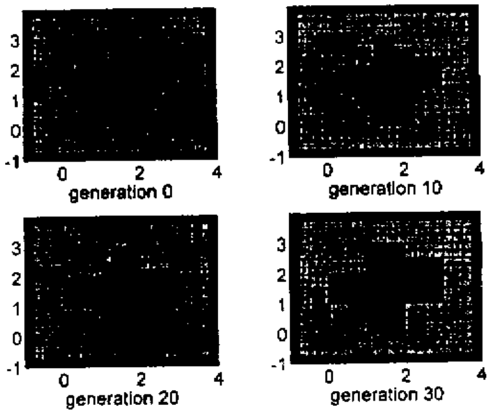

Fig.11 (b) (continued)

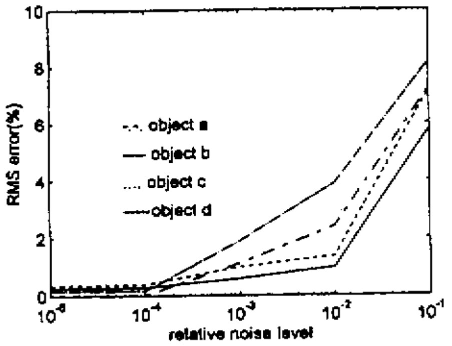

Fig.12 Reconstructed error against relative noise level
for objects A , B , C and D.